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Letter

Search for a heavy neutral particle decaying into an electron and a muon using 1 fb^{-1} of ATLAS data

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Abstract A search is presented for a high mass neutral particle that decays directly to the $e^\pm\mu^\mp$ final state. The data sample was recorded by the ATLAS detector in $\sqrt{s} = 7$ TeV pp collisions at the LHC from March to June 2011 and corresponds to an integrated luminosity of 1.07 fb^{-1}. The data are found to be consistent with the Standard Model background. The high $e^\pm\mu^\mp$ mass region is used to set 95% confidence level upper limits on the production of two possible new physics processes: tau sneutrinos in an R-parity violating supersymmetric model and Z'-like vector bosons in a lepton flavor violating model.

Short-lived particles that decay into two oppositely signed leptons of different flavors, $e^\pm\mu^\mp$ ($e\mu$), $e^\pm\tau^\mp$ ($e\tau$), or $\mu^\pm\tau^\mp$ ($\mu\tau$), are predicted by a number of extensions to the Standard Model (SM). Examples include sneutrinos in R-parity violating (RPV) supersymmetric (SUSY) models [1], and extra gauge Z' bosons with lepton flavor violating (LFV) interactions [2]. This Letter reports a search for an excess of high invariant mass $e\mu$ ($m_{e\mu}$) events over SM predictions in pp collisions at $\sqrt{s} = 7$ TeV at the LHC. The $e\mu$ final state is chosen due to its clean detector signature and low SM background in the high $m_{e\mu}$ region. Similar searches with the $e\mu$ final state have been reported previously by the CDF, D0 and ATLAS Collaborations [3–8]. In this Letter, we report an updated search with a data sample approximately 30 times larger than used for the previous ATLAS search [8] with improved sensitivity to new physics.

The ATLAS detector [9] is a multi-purpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near 4π coverage in solid angle.[1] The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field and by a hermetic calorimeter system, which provides three-dimensional reconstruction of particle showers up to $|\eta| < 4.9$. For $|\eta| < 2.5$, the electromagnetic calorimeter is finely segmented and plays an important role in electron identification. The muon spectrometer (MS) is based on three large superconducting toroids arranged with an eight-fold azimuthal coil symmetry around the calorimeters. Three stations of drift tubes and cathode strip chambers enable precise muon track measurements, and resistive-plate and thin-gap chambers provide muon triggering capability.

The data sample used in this analysis was collected using single lepton (e or μ) triggers, between March and June 2011. The total integrated luminosity is 1.07 ± 0.04 fb^{-1} [10, 11]. The trigger efficiency is measured to be 100%, with a precision of 1%, for $e\mu$ candidates that pass the default selection criteria described below.

To select $e\mu$ candidates, the electron candidate is required to have $p_T > 25$ GeV and to have pseudorapidity $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$. It is further required to pass the "medium" [12] quality definition, which is based on the calorimeter shower shape, track quality, and track matching with the calorimeter cluster. In addition, the electron is required to be isolated in the calorimeter with $E_T^{\Delta R<0.4} < 10$ GeV, where $E_T^{\Delta R<0.4}$ is defined as the transverse energy deposited in the calorimeter within a cone of radius $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ around the electron cluster. Corrections have been applied to account for energy leakage from the electron and energy deposition inside the isolation cone due to additional pp collisions. The muon candidate must be reconstructed in both the ID and the MS, and

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upward. Cylindrical coordinates (R, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

have $p_T > 25$ GeV and $|\eta| < 2.4$. Furthermore, the muon is required to be isolated in the ID with $p_T^{\Delta R<0.4} < 10$ GeV, where $p_T^{\Delta R<0.4}$ is defined as the scalar sum of the p_T of tracks associated to the primary vertex, within a cone of radius $\Delta R = 0.4$ around the muon track. Only tracks with $p_T > 1$ GeV are used. Furthermore, only electrons separated from muons by $\Delta R > 0.2$ are considered.

The $e\mu$ candidate events are required to have exactly one electron and one muon with opposite charge satisfying the above selection criteria. Furthermore, events have to contain at least one primary vertex reconstructed with at least three associated tracks of $p_T > 500$ MeV.

The SM processes that can produce an $e\mu$ signature can be divided into two categories: processes such as $Z/\gamma^* \to \tau\tau$, $t\bar{t}$, single top, WW, WZ and ZZ, which can produce electrons and muons in the final state, and processes, referred to as fake background in this Letter, such as $W/Z+\gamma$, $W/Z+$jets and multijet events where the photon or one or two jets are reconstructed as leptons.

The contributions from processes listed in the first category as well as photon-related backgrounds are estimated using Monte Carlo (MC) samples generated at $\sqrt{s} = 7$ TeV. The detector response simulation [13] is based on the GEANT4 program [14]. Lepton reconstruction and identification efficiencies, energy scales and resolutions in the MC are corrected to the corresponding values measured in the data in order to improve the modeling of the background. The MC predictions are normalized to the data sample based on the integrated luminosity and cross sections of various physics processes. Top production is generated with MC@NLO [15–17] for $t\bar{t}$ and single top, the Drell–Yan process is generated with PYTHIA [18], and the diboson processes are generated with HERWIG [19, 20]. Higher order corrections have been applied to the cross sections predicted by these generators [21–23]. The $W/Z+\gamma$ contribution in the fake background comes from the $W(\to \mu\nu)\gamma$ and $Z(\to \mu\mu)\gamma$ processes, where the photon is reconstructed as an electron. This background is estimated using events generated with MADGRAPH [24].

The uncertainties for the $t\bar{t}$ and single top cross sections are taken to be 10% [25, 26] and 9% [27], respectively. The cross sections for $W/Z+\gamma$, $Z/\gamma^* \to \tau\tau$, WW, WZ and ZZ are assigned uncertainties of 10%, 5%, 7%, 7%, and 5%, respectively; these uncertainties arise from the choice of PDF, from factorization and renormalization scale dependence and from α_s variations. The integrated luminosity uncertainty and other smaller systematic uncertainties from the lepton trigger, reconstruction and identification efficiencies, energy (momentum) scale and resolution have been added in quadrature and are included in the total uncertainty.

The remaining fake backgrounds arise from the $W/Z+$jets and multijet processes, where leptons are present from b- or c-hadron decays or at least one jet is misidentified as a lepton. Such lepton candidates are collectively referred to as "non-prompt leptons" in this Letter. These jet fake backgrounds account for ∼30% of the expected $e\mu$ data yield and are estimated from data using a 4×4 matrix background estimation method described below. A looser lepton quality selection (called loose lepton here) is defined for each lepton type in addition to the default quality selection (called tight lepton here). For loose muons, the isolation requirement is dropped. For loose electrons, the "loose" electron identification criteria as defined in Ref. [12] are used and the isolation requirement is also dropped. The tight and loose lepton selections are then used to classify events where both leptons pass the loose requirements into four categories, depending on whether both leptons subsequently pass the tight requirement (N_{pp}), only one lepton fails the tight requirement and the other lepton passes the tight requirement (N_{pf} or N_{fp}), or both leptons fail the tight requirement (N_{ff}). The sample composition can be estimated by solving a linear system of equations: $(N_{pp}, N_{pf}, N_{fp}, N_{ff})^T = \epsilon(N_{e\mu}, N_{e\mu^\dagger}, N_{e^\dagger\mu}, N_{e^\dagger\mu^\dagger})^T$, where $N_{e\mu}$ (or $N_{e^\dagger\mu^\dagger}$) is the number of events with two prompt leptons (or two non-prompt leptons), while $N_{e\mu^\dagger}$ and $N_{e^\dagger\mu}$ are the numbers of events with one prompt lepton and one non-prompt lepton. The matrix ϵ contains the probabilities for a loose quality lepton to pass the tight quality selection for both prompt and non-prompt leptons. The probability for prompt leptons (non-prompt leptons) is estimated by applying the loose and tight selections on $Z/\gamma^* \to ee/\mu\mu$ events (a sample of dijet events). To take into account the lepton p_T dependence of the two probabilities, the matrix equation is inverted for each event, giving four weights, corresponding to the four combinations of prompt and non-prompt leptons. These weights are then summed over all events to yield the total number of events with one or more non-prompt leptons. The overall jet fake background is found to be 1175 ± 32 (stat) events. The breakdown of these contributions is estimated to be $N_{e\mu^\dagger} = 375 \pm 30$ (stat), $N_{e^\dagger\mu} = 89 \pm 13$ (stat) and $N_{e^\dagger\mu^\dagger} = 711 \pm 8$ (stat). The overall systematic uncertainty of 10% comes mainly from the uncertainty on the probability for a loose quality non-prompt muon to pass the tight quality selection.

Table 1 shows the number of events selected in data and the estimated background contributions with their uncertainties (both statistical and systematic uncertainties are included). A total of 4053 $e\mu$ candidates are observed, while the expectation from SM processes is 4145 ± 250 events. The $m_{e\mu}$ distribution is presented in Fig. 1 for data and background contributions. The distribution of observed events is compared to the expected background using a Kolmogorov–Smirnov test with statistical uncertainties only [28, 29]. The test probability is 56%, consistent with the absence of a new physics signal.

Table 2 shows the numbers of observed and predicted background events in eleven high $e\mu$ mass regions. Good

Table 1 Estimated backgrounds in the selected sample, together with the observed event yield. The total integrated luminosity is 1.07 fb^{-1}

Process	Number of events
$t\bar{t}$	1580 ± 170
Jet fake	1175 ± 120
$Z/\gamma^* \to \tau\tau$	750 ± 60
WW	380 ± 31
Single top	154 ± 16
$W/Z + \gamma$	82 ± 13
WZ	22.4 ± 2.3
ZZ	2.48 ± 0.26
Total background	4145 ± 250
Data	4053

Table 2 Estimated total backgrounds in the selected sample, together with the observed event yields for 11 high $e\mu$ mass regions

$m_{e\mu}$	Data	SM prediction
>200 GeV	286	288 ± 22
>250 GeV	152	136 ± 11
>300 GeV	70	67 ± 6
>350 GeV	35	34.0 ± 3.0
>400 GeV	22	17.7 ± 1.7
>450 GeV	10	10.5 ± 1.2
>500 GeV	7	6.8 ± 0.9
>550 GeV	3	4.3 ± 0.6
>600 GeV	3	2.4 ± 0.4
>650 GeV	1	1.49 ± 0.31
>700 GeV	0	1.07 ± 0.25

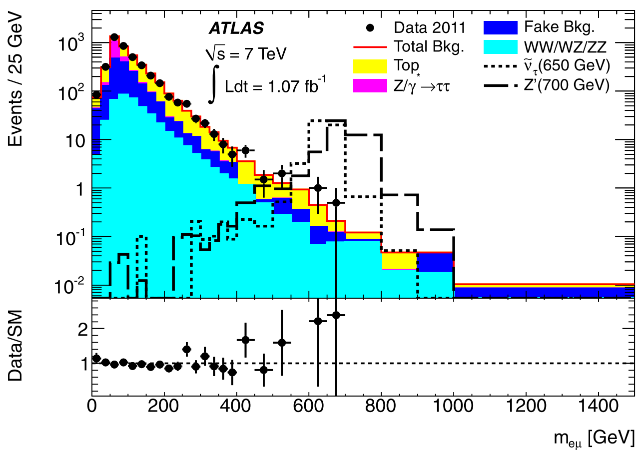

Fig. 1 Observed and predicted $e\mu$ invariant mass distributions. Signal simulations are shown for $m_{\tilde{\nu}_\tau} = 650$ GeV and $m_{Z'} = 700$ GeV. The couplings $\lambda'_{311} = 0.10$ and $\lambda_{312} = 0.05$ are used for the RPV $\tilde{\nu}_\tau$ model. The production cross section is assumed to be the current published limit of 0.178 pb for the LFV Z' model [8]. The ratio plot at the bottom includes only statistical uncertainties

agreement is found for all mass regions and no statistically significant data excess is observed. Limits are set on the contributions of new physics processes to the high mass region from two scenarios: the production of $\tilde{\nu}_\tau$ in an RPV SUSY model and of an LFV Z' in extra-gauge boson models.

The process $d\bar{d} \to \tilde{\nu}_\tau \to e\mu$ in a SUSY RPV model is considered. The RPV sneutrino couplings allowed in the supersymmetric Lagrangian are $\frac{1}{2}\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}_k$, where L and Q are the lepton and quark $SU(2)$ doublet superfields, and E and D denote the singlet fields for charged leptons and down type quarks, respectively. The indices $i, j, k = 1, 2, 3$ refer to the fermion generation numbers. The coupling constants λ satisfy $\lambda_{ijk} = -\lambda_{jik}$. Only the tau sneutrino is considered in this Letter since stringent limits already exist on the electron sneutrino and muon sneutrino [1]. By fixing all RPV couplings except λ'_{311} ($\tilde{\nu}_\tau$ to $d\bar{d}$) and λ_{312} ($\tilde{\nu}_\tau$ to $e\mu$) to zero, and assuming that $\tilde{\nu}_\tau$ is the lightest supersymmetric particle, the contributions to the $e\mu$ final state originate from the $\tilde{\nu}_\tau$ only. The cross section is 0.154 pb for $m_{\tilde{\nu}_\tau} = 650$ GeV, $\lambda'_{311} = 0.10$ and $\lambda_{312} = \lambda_{321} = 0.05$ [30, 31]. The total decay width is $\Gamma_{\tilde{\nu}_\tau} = (3\lambda'^2_{311} + 2\lambda^2_{312})m_{\tilde{\nu}_\tau}/16\pi$. Using couplings that are consistent with the current limits, the decay width is less than 1 GeV for $m_{\tilde{\nu}_\tau} = 1$ TeV, which is well below the contribution from detector resolution. MC samples with $\tilde{\nu}_\tau$ masses ranging from 0.1 to 2 TeV are generated with HERWIG [19, 20, 32].

An $e\mu$ resonance also appears in models containing a heavy neutral gauge boson, Z' [33], with non-diagonal lepton flavor couplings. Rare muon decay searches have placed extremely stringent limits on the combination of the mass and the coupling to ee and $e\mu$ in such models [2]. The $e\mu$ searches at hadron colliders are not able to match the sensitivity of dedicated $\mu \to e$ conversion experiments. A limit on the production cross section times branching ratio to $e\mu$ is placed on the Z'-like boson model to represent the production of vector particles that can decay to the $e\mu$ final state. To calculate the efficiency and acceptance, the Z' is assumed to have the same quark and lepton couplings as the SM Z except a non-zero Z' to $e\mu$ coupling, which is assumed to be the same as the Z' to ee coupling. The cross section is 0.61 pb for $m_{Z'} = 700$ GeV [34]. MC samples with Z' masses ranging from 0.7 to 2 TeV are generated with PYTHIA.

Both $\tilde{\nu}_\tau$ and Z' samples are processed through the standard chain of the ATLAS simulation and reconstruction. The overall product of acceptance and efficiency is 36% for $m_{\tilde{\nu}_\tau} = 100$ GeV and increases to 64% for $m_{\tilde{\nu}_\tau} = 1$ TeV. The corresponding number is $\sim 60\%$ for Z' with mass $m_{Z'} = 700$ GeV to $m_{Z'} = 2$ TeV. The predicted $m_{e\mu}$ distributions for a $\tilde{\nu}_\tau$ with $m_{\tilde{\nu}_\tau} = 650$ GeV and a Z' with $m_{Z'} = 700$ GeV are also shown in Fig. 1.

The $m_{e\mu}$ spectrum is examined for the presence of a new heavy particle. For each assumed $m_{\tilde{\nu}_\tau}$ value in the range 100 GeV to 2 TeV, a search region, which depends on the simulated $e\mu$ mass resolution, is used.[2] The number of observed and predicted background and signal events in each search range are used to set an upper limit on $\sigma(pp \to \tilde{\nu}_\tau) \times \mathrm{BR}(\tilde{\nu}_\tau \to e\mu)$. A Bayesian method [35] is used with a uniform prior for the signal cross section for a given $m_{\tilde{\nu}_\tau}$. Figure 2a shows the expected and observed 95% confidence level (C.L.) limits, as a function of $m_{\tilde{\nu}_\tau}$, together with the limits previously published by ATLAS [8], which were based on 35 pb^{-1} of data, and the expected ± 1 and ± 2 standard deviation uncertainty bands. For a $\tilde{\nu}_\tau$ with a mass of 100 GeV (1 TeV), the limit on the cross section times branching ratio is 135 (4.5) fb. The limits obtained extend 7 (34) times beyond the previous ATLAS results. The theoretical cross sections for $\lambda'_{311} = 0.10$, $\lambda_{312} = 0.05$ and $\lambda'_{311} = 0.11$, $\lambda_{312} = 0.07$ are also shown. Tau sneutrinos with a mass below 1.32 (1.45) TeV are excluded, assuming coupling values $\lambda'_{311} = 0.10$ and $\lambda_{312} = 0.05$ ($\lambda'_{311} = 0.11$ and $\lambda_{312} = 0.07$). The limits are significantly better than the limits from the previous ATLAS analysis using 35 pb^{-1} of data. The 95% C.L. observed upper limits on λ'_{311} as a function of $m_{\tilde{\nu}_\tau}$ are shown in Fig. 2b for three values of λ_{312}, together with the exclusion region obtained from the D0 experiment [7] and previously by the ATLAS experiment [8]. The limits on λ'_{311} are tighter than the D0 results for $m_{\tilde{\nu}_\tau} > 270$ GeV sneutrinos assuming $\lambda_{312} = 0.07$. Better sensitivity can be obtained for $m_{\tilde{\nu}_\tau} < 270$ GeV by applying selection cuts on missing transverse energy and number of jets in the event to improve the signal and background ratio, but it will make the search model-dependent.

A similar method is used to set limits on the LFV Z'-like vector boson; however, as opposed to the sneutrino limits, a unique mass window is defined for each potential signal mass. The 95% C.L. upper limits on $\sigma(pp \to Z') \times \mathrm{BR}(Z' \to e\mu)$ are shown in Fig. 3. The expected limit is the same as the observed limit for the high mass points because both the median background event count expectation and the observed number of events are zero. For a Z' with mass of 0.7 TeV (1.0 TeV), the limit on the cross section times branching ratio is 9.6 fb (4.8 fb). This result improves upon previous ATLAS limits by roughly a factor of 20 (40).

In conclusion, a search has been performed for high mass $e\mu$ events using pp collision data at $\sqrt{s} = 7$ TeV recorded by the ATLAS detector. The observed $m_{e\mu}$ distribution is

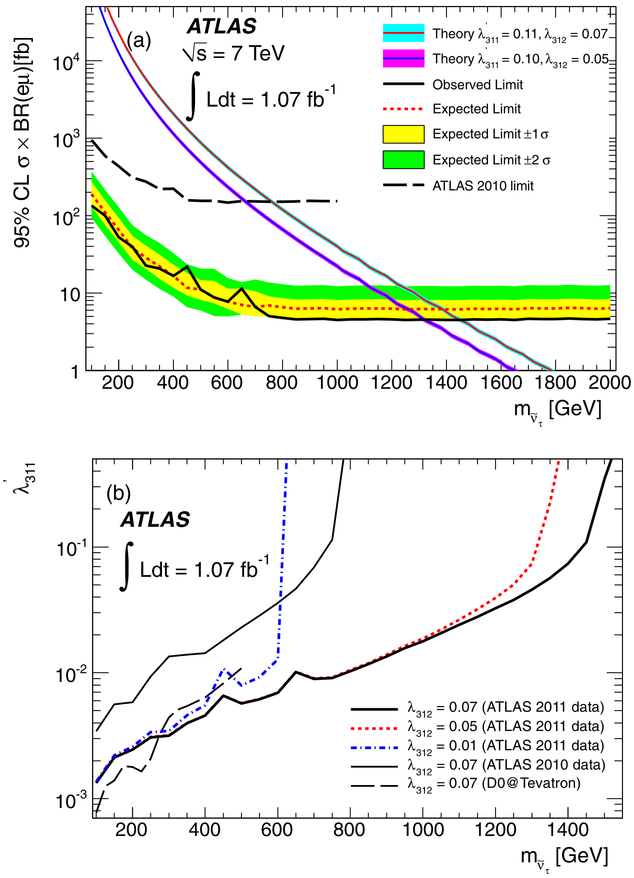

Fig. 2 (**a**) The observed 95% C.L. upper limits on $\sigma(pp \to \tilde{\nu}_\tau) \times \mathrm{BR}(\tilde{\nu}_\tau \to e\mu)$ as a function of $m_{\tilde{\nu}_\tau}$. The expected limits are also shown together with the expected ± 1 and ± 2 standard deviation uncertainty bands. The previous ATLAS published limit and two theoretical cross sections for $\lambda'_{311} = 0.10$, $\lambda_{312} = 0.05$ and $\lambda'_{311} = 0.11$, $\lambda_{312} = 0.07$ calculated using MADGRAPH with next-to-leading order k-factors applied [30, 31] are also shown. (**b**) The 95% C.L. upper limits on the λ'_{311} coupling as a function of $m_{\tilde{\nu}_\tau}$ for three values of λ_{312}. The regions above the three curves represent ranges of λ'_{311} values that are excluded. These results are compared with the exclusion regions obtained from the D0 experiment and the previously published ATLAS analysis. The cross section times branching ratio for $pp \to e\mu$ is proportional to $\lambda'^2_{311}\lambda^2_{312}/(3\lambda'^2_{311} + 2\lambda^2_{312})$, which causes the weak dependence of the λ'_{311} limits on λ_{312} for low mass tau sneutrinos

found to be consistent with SM predictions. With no evidence for new physics, 95% C.L. exclusion limits are placed on the production cross sections and RPV coupling values of the tau sneutrinos in an RPV SUSY model, and tau sneutrinos with a mass below 1.32 (1.45) TeV are excluded, assuming coupling values $\lambda'_{311} = 0.10$ and $\lambda_{312} = 0.05$ ($\lambda'_{311} = 0.11$ and $\lambda_{312} = 0.07$). The results presented here are the most stringent results to date for $m_{\tilde{\nu}_\tau} > 270$ GeV. More stringent constraints are also set on the production cross sections of Z' bosons in an LFV model. These two benchmark models can be used to represent the production of any narrow scalar and vector particles that can decay to the $e\mu$ final state.

[2]The search region is normally defined to be $(m_{\tilde{\nu}_\tau} - 3\sigma, m_{\tilde{\nu}_\tau} + 3\sigma)$, where σ is the expected $m_{e\mu}$ resolution (e.g., $\sigma = 11$ GeV for $m_{\tilde{\nu}_\tau} = 400$ GeV). If $m_{\tilde{\nu}_\tau} - 3\sigma < 700$ GeV and $m_{\tilde{\nu}_\tau} + 3\sigma > 700$ GeV, the region above $m_{\tilde{\nu}_\tau} - 3\sigma$ is used. If $m_{\tilde{\nu}_\tau} - 3\sigma > 700$ GeV, the region above 700 GeV is used. The mass window changes around 700 GeV because the MC statistics is not sufficient in the $m_{e\mu} > 700$ GeV region.

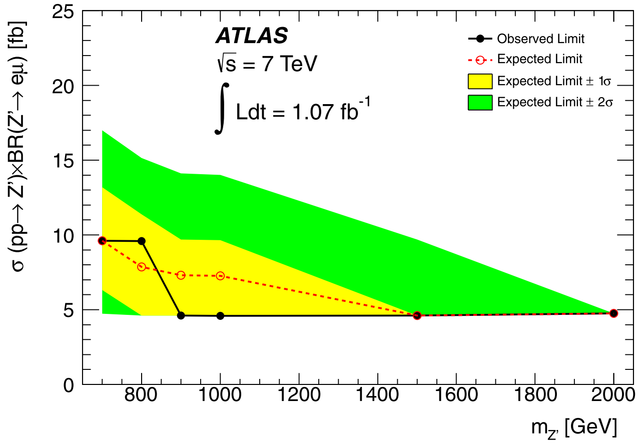

Fig. 3 The observed 95% C.L. upper limits on $\sigma(pp \to Z') \times \mathrm{BR}(Z' \to e\mu)$. The expected limits are also shown together with the expected ±1 and ±2 standard deviation uncertainty bands. The observed and expected limits overlap as discussed in the text

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